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X-RAY CONSTRAINTS ON IONIZING PHOTONS FROM ACCRETING BLACK HOLES AT Z ~ 6[1]

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ABSTRACT

Using an X-ray stacking procedure, we provide a robust upper limit to the X-ray luminosity per object of a set of 54 $z \approx 5.8$ galaxy candidates in the *Hubble* Ultra Deep Field (HUDF), which is within the 1 Ms-exposure *Chandra* Deep Field-South (CDF-S). With an effective total exposure of 44 Ms for the stack, the 3σ flux-density limit of $2.1 \times 10^{-17}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ (soft-band) gives a 3σ upper-limit luminosity of $L_{\mathrm{X}} = 8 \times 10^{42}\,\mathrm{erg\,s^{-1}}$ per object at a rest-frame hard energy range of ~ 3–$14\,\mathrm{keV}$ at $z \approx 5.8$ for a photon index of $\Gamma = 2$. For an active accreting black hole (or "mini-quasar") emitting at the Eddington luminosity ($\eta_{\mathrm{Edd}} = 1$), and the Sazonov et al. average-QSO spectral energy distribution, we calculate an upper limit on the black hole mass, $M_{\mathrm{bh}} < 3 \times 10^6\,\eta_{\mathrm{Edd}}^{-1}\,M_{\odot}$ (3σ). The X-ray limit further implies an upper limit on the rate density of UV ionizing photons from accreting black holes at that redshift, $\dot{n}_{\mathrm{ioniz}} < 2 \times 10^{51}\,\mathrm{s^{-1}\,Mpc^{-3}}$ (3σ), which is less than 1/10 of the number needed to ionize the universe. Because the constraint is anchored in the rest-frame hard X-ray regime, a steeper spectrum for "mini-quasars" would imply relatively *fewer* ionizing UV photons. Unless there are large populations of active black holes around this mass that are *unassociated* with luminous galaxies, mini-quasars do not appear to contribute significantly to the budget of ionizing photons at $z \approx 6$.

Subject headings: galaxies: formation – galaxies: evolution – galaxies: high-redshift – early universe – X-rays: galaxies

1. INTRODUCTION

The identification of the epoch or epochs of reionization is not a solved problem, though there is tension between the high redshift ($z_{\mathrm{reion}} \sim 10$–$17$) of reionization implied by the WMAP results (Spergel et al. 2003; Kogut et al. 2003) and the lower redshift ($z_{\mathrm{reion}} \approx 6$) suggested by the detection of the Gunn-Peterson trough in $z \approx 6$ luminous QSOs by SDSS (Becker et al. 2001; Djorgovski et al. 2001). These observations suggest that the transition from an opaque to a fully reionized universe must have at least *ended* by $z \approx 6$. One of the challenges faced today is to identify the sources of the ionizing photons (e.g. Loeb & Barkana 2001; Stiavelli et al. 2004a, and references therein), which are still unaccounted for from observed stellar and accreting black-hole ("active") populations.

The Advanced Camera for Surveys (ACS; Benítez et al. 2004) on the *Hubble Space Telescope* (*HST*) has made routine the discovery of candidate galaxies at redshift $z \approx 6$ (Bunker et al. 2003; Bouwens et al. 2003; Stanway et al. 2003, 2004; Dickinson et al. 2004; Giavalisco et al. 2004b). These objects are identified by an extension of the "Lyman Break" technique (Steidel & Hamilton 1992; Steidel et al. 1996), whereby the opacity from neutral hydrogen in the intergalactic medium (or the Lyman-α forest) suppresses the flux at wavelengths shortward of the Lyman break (Madau et al. 1996), or shortward

of the Lyman-α emission (Dickinson et al. 2004)). The *HST*/ACS i_{775} and z_{850} filters bracket Lyman-α ($\lambda_{\mathrm{rest}} = 1216\,\text{Å}$) around $z \approx 5.8$, so searches for "i-dropouts" will isolate candidate galaxies around that redshift (Stanway et al. 2003; Dickinson et al. 2004), as well as possible "interlopers" in the guise of cool stellar dwarfs or faint evolved galaxies at $z \approx 1$–2. Some of these high-redshift candidate galaxies have been confirmed spectroscopically from the ground, and from the G800L grism of ACS (Pirzkal et al. 2004; Malhotra et al. 2004).

Using data from the ACS-based *Hubble* Ultra Deep Field (HUDF; Beckwith et al. 2004), Bunker et al. (2004) identified 54 spatially-resolved i-dropout candidates to $z_{850} \approx 28.5$. It is still an open question whether some combination of these galaxies, possibly with the contribution of as yet unveiled populations, have enough energetic photons to ionize (or keep ionized) the universe at this epoch (Bunker et al. 2004; Stiavelli et al. 2004b).

The need to account for the large number of required ultraviolet photons for ionization (Madau, Haardt, & Rees 1999) has given rise to a broad range of proposed sources, ranging from known candidates (stellar and active sources) to exotic ones (e.g. decaying heavy neutrinos, Hansen & Haiman 2004). The stellar sources can be divided broadly into two categories. The first-generation "metal-free" stars (Abel et al. 2002), which may arise in $M_{\mathrm{dm}} \gtrsim 10^5\,M_{\odot}$ dark matter halos, are expected to have masses of $M_* \gtrsim 60\,M_{\odot}$[4]. These stars, though rare, may produce enough photons to contribute most or all of the UV

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[4] Such stars with masses in the range $M_* \sim 60$–$140\,M_{\odot}$, and $M_* > 260\,M_{\odot}$ are predicted to collapse directly to a black hole (Heger et al. 2003), with $M_* \sim 140$–$260\,M_{\odot}$ stars annihilating themselves through pair-creation processes. Such collapsed stars may be the seeds of the "mini-quasar" black holes discussed below.

photons needed to ionize the universe even at very early times ($z \sim 20$; e.g. Somerville & Livio 2003). If such objects are to be found at $z \sim 6$, it is unlikely that significant amounts of X-ray emission would be associated with them. Population II stars, which may also contribute to the ionizing radiation budget at high redshift, could have associated X-ray emission from X-ray binaries that result from different modes of star formation (Grimm et al. 2003). Though such relatively locally determined relations may not hold over all time, they can be used to explore relevant limits to star formation rates at high redshift.

It is plausible that many of the first collapsed objects produced black holes of some mass, that could then be sources of energy. This possibility is potentially attractive as a source of energetic photons, particularly if there are mechanisms for self-regulation of their growth (Wyithe & Loeb 2003). The mass-increase e-folding time of black holes emitting at their Eddington luminosities, the Salpeter timescale, is $T_{\mathrm{Salp}} \approx 1 \times 10^8 \, (\epsilon/0.30)^{-1}$ yr, where ϵ is the energy conversion efficiency (Elvis et al. 2002; Gammie et al. 2004). The T_{Salp} is independent of the black hole mass. If the active lifetime of an accreting black hole at $z \sim 6$ is several times T_{Salp}, so that the probability of any one host galaxy being observed while "active" is high, it is possible that the majority of galaxies hosting black holes could be observed during an active stage.

In this paper we use one plausible set of dropout-selected galaxies at $z \approx 5.8$, described in § 2. None of these sources are individually detected in the deep *Chandra* observations in that field. We therefore construct an extremely deep stack of the full sample, as set out in § 3, and compute an upper limit to the average X-ray luminosity for each galaxy. This number is cast against proposed sources of ionizing photons at that redshift in § 4, and the possible utility of these limits are discussed in § 5. We assume the concordance cosmology parameters of a flat universe with $\Omega_\Lambda = 1 - \Omega_m = 0.7$, and $H = 70 \, h_{70} \, \mathrm{km \, s^{-1} \, Mpc^{-1}}$.

2. THE HUDF AND HIGH-REDSHIFT CANDIDATES

The HUDF[5] is a 11.3 arcmin^2 ACS-based survey of a single extremely deep field observed within the GOODS-South[6] field (Giavalisco et al. 2004a). The observations have been made in the same filters as the GOODS project, B_{435}, V_{606}, i_{775} and z_{850}, and reach 10σ depths of $z_{850} \approx 28.5$ (AB). This is also the 1 Ms *Chandra* Deep Field-South (CDF-S) field, which reaches on-axis flux density limits of $5.5 \times 10^{-17} \, \mathrm{erg \, s^{-1} \, cm^{-2}}$ in the soft-band (0.5–2 keV) and $4.5 \times 10^{-16} \, \mathrm{erg \, s^{-1} \, cm^{-2}}$ in the hard-band (2–8 keV; Giacconi et al. 2002).

By virtue of the dropout selection with the i_{775} and z_{850} bandpasses, the redshift distribution/selection function of the high-redshift galaxies is quite narrow, centered around $z \approx 5.8$. The candidate list in Bunker et al. (2004) is a lower limit on the total number visible in the HUDF, because of the very conservative signal-to-noise requirements applied in the detection band. At the same time, by the strong color criterion, there should be few foreground ($z \approx 2$) galaxies. Therefore we adopt the

[5] http://www.stsci.edu/hst/udf/
[6] http://www.stsci.edu/science/goods/

Band	Counts	T_{eff} (Ms)	Rate (10^{-6})	f_{x} (3σ) (10^{-17})	L_{x} (3σ) (10^{43})
(1)	(2)	(3)	(4)	(5)	(6)
0.5–8	319.1 ± 19.8	44.3	7.20 ± 0.45	8.0 ± 0.5	3.16
0.5–2	114.3 ± 11.9	44.1	2.59 ± 0.27	2.1 ± 0.2	0.83
2–8	204.7 ± 15.7	43.5	4.70 ± 0.36	11.7 ± 0.9	4.68

(1) Observed-frame energy band E_{obs} in keV; (2) Total aperture counts; fractional counts are due to fractional detection cells within the apertures; (3) Effective exposure time; (4) Exposure-corrected count rate in $10^{-6} \, \mathrm{s^{-1}}$; (5) X-ray fluxes in erg cm^{-2} s^{-1}, $\Gamma = 2$; (6) Rest-frame X-ray luminosities at energy bands $(1 + z) \times E_{\mathrm{obs}}$ for $z = 5.8$, in erg s^{-1}, for $\Gamma = 2$.

tabulated list of candidates directly from Bunker et al. (2004), several of which have already been spectroscopically confirmed to be at the claimed redshift range.
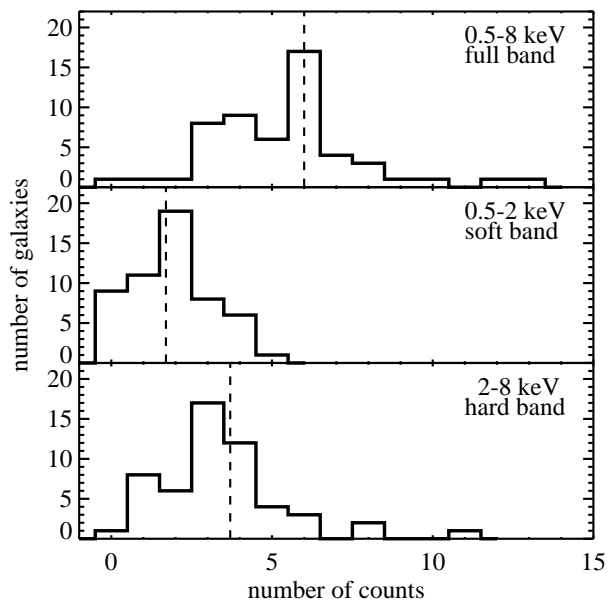

FIG. 1.— The distribution of X-ray counts for all candidate $z \approx 5.8$ galaxies. The vertical dashed lines mark the mean background count levels in each band, as determined from Monte Carlo simulations with 10,000 trials.

3. THE X-RAY STACK PROCEDURE AND RESULTS

Stacking the X-ray images of individually undetected objects has offered exceptional insights into the nature of star formation and activity in otherwise X-ray-invisible extremely distant objects (e.g. Alexander et al. 2002a,b; Nandra et al. 2002; Reddy & Steidel 2004). In the present work, we target the positions of all the sources described in the previous section. A search radius of 1.5 times the error in the X-ray position was applied to match each of the optical positions with the X-ray source catalogs by Giacconi et al. (2002) and Bauer et al. (2004). For each object position, exposure-corrected counts were extracted within the 90% encircled-energy (EE) radii in the full (0.5–8 keV), soft (0.5–2 keV), and hard (2–8 keV) energy bands. Also at each position, in order to quantify the significance (or lack thereof) of the

counts measurement, we perform Monte Carlo (MC) simulations with 10,000 trials using source-free circular regions of $20\,\mathrm{arcsec}$ radius around each galaxy. The net aperture counts, then, are obtained by subtracting the mean value of the (near-Gaussian) MC distribution from the number of average aperture counts. Details of the stacking procedure are discussed in Immler et al. (2004).

Using the above apertures to count the number of X-ray photons at each galaxy position, we detect 319 counts in total, distributed as shown in Fig. 1 and tabulated in Table 1. The exposure-corrected count rate in the full band is $\sim 2.6 \times 10^{-6}\,\mathrm{s}^{-1}$ in the soft band, with a total effective exposure time of $44.1\,\mathrm{Ms}$. There is no formal X-ray detection in the stacked data. Assuming $z = 5.8$, a power law spectral energy distribution (SED) with a photon index of $\Gamma = 2$, and a foreground absorbing column density of $N_{\mathrm{HI}} = 8.0 \times 10^{19}\,\mathrm{cm}^{-2}$ (Stark et al. 1992), we find a band-corrected $3\,\sigma$ limit on the luminosity *per galaxy* of $L_{\mathrm{X}} < 8.3 \times 10^{42}\,\mathrm{erg\,s}^{-1}$ $(3\,\sigma)$ in the rest-frame energy band $(1+z) \times (0.5\text{--}2\,\mathrm{keV}) \approx 3\text{--}14\,\mathrm{keV}$. The conversion between counts and flux is not very sensitive to the assumed spectral properties — a photon index of $\Gamma = 1.7$ instead of $\Gamma = 2$ gives a flux which is $\lesssim 5\%$ lower. As the k-correction for a power law with photon index Γ is $k(z) = (1 + z)^{\Gamma - 2}$, the X-ray luminosity constraints can correspondingly be lower by $\sim 40\%$ for $\Gamma = 1.7$.
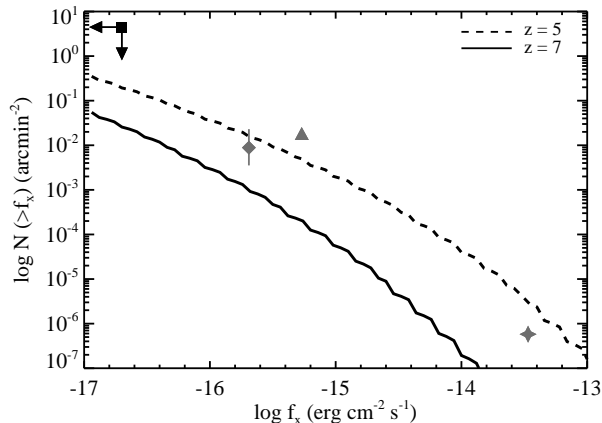

FIG. 2.— The cumulative surface density of X-ray emitting active objects versus flux limit. The model lines are drawn for quasar number counts at redshifts of $z = 5$ (dashed line) and $z = 7$ (solid line) from Wyithe & Loeb (2003). The limits determined from this study for $z \approx 5.8$ are shown (black box). The counts from Barger et al. (2003) at $z > 5$ (diamond), Cristiani et al. (2004) at $3.5 \gtrsim z \gtrsim 5.2$ (triangle), and Fan et al. (2004) at $z \gtrsim 5.7$ (star) are shown for comparison.

4. HIGH-REDSHIFT SOURCES OF IONIZING PHOTONS

There is still no consensus on the source or sources of ionizing photons at redshifts $z \sim 6$ and beyond (see Loeb & Barkana 2001, for a review of candidate populations), though it is possible that a complex reionization history (Cen 2003; Hui & Haiman 2003) could have been driven by different combinations of ionizing sources at different times (e.g. Somerville & Livio 2003; Sokasian et al. 2003, 2004; Madau et al. 2004). The highest redshift where there are presently extensive data is $z \approx 6$. The success of identifying how the universe stays ionized at that redshift is mixed (Yan & Windhorst

2004; Bunker et al. 2004; Stiavelli et al. 2004b). In this section, we consider the implications of our measured limits.

4.1. *Star formation*

Without making any corrections for obscuration, the Kennicutt (1998) relation $\mathrm{SFR}_{\mathrm{UV}}(M_{\odot}\,\mathrm{yr}^{-1}) = 1.4 \times 10^{-28} L_{\nu}(\mathrm{erg\,s}^{-1}\,\mathrm{Hz}^{-1})$ (for a Salpeter IMF) gives a typical $\mathrm{SFR}_{\mathrm{UV}} \approx 10\,M_{\odot}\,\mathrm{yr}^{-1}$ for each galaxy, where we have used the z_{850} photometry ($\lambda_{\mathrm{rest}} \approx 1400\,\text{Å}$). At low redshift, there is a well-explored association between star formation rates and X-ray luminosity, driven by the aggregate effect of low- and high-mass X-ray binaries (LMXBs and HMXBs, respectively), which are formed at different stages of stellar evolution. At star formation rates above several $M_{\odot}\,\mathrm{yr}^{-1}$, promptly-formed HMXBs dominate, and Grimm et al. (2003) find $\mathrm{SFR}_{\mathrm{X}}\,(M_{\odot}\,\mathrm{yr}^{-1}) = L_{2-8\mathrm{keV}} / (6.7 \times 10^{39}\,\mathrm{erg\,s}^{-1})$. Using the rest-frame hard X-ray limit, we calculate $\mathrm{SFR}_{\mathrm{X}} < 1100\,M_{\odot}\,\mathrm{yr}^{-1}$ $(3\,\sigma)$. This limit is therefore not useful compared to the measurements from the rest-UV (Bunker et al. 2004; Stiavelli et al. 2004b), and we do not discuss it further.

4.2. *Accreting black holes*

There is theoretical motivation for black hole accretion-powered "mini-quasars" at high redshift (e.g. Madau et al. 2004). These could begin forming at very early times ($z \gtrsim 20$) from the collapse of first-generation massive stars, and grow substantially in mass by $z \approx 6$. Whereas the comoving space density of *supermassive* ($M_{\mathrm{bh}} \gtrsim 10^{9} M_{\odot}$) black holes at this redshift is exceedingly small (Fan et al. 2003), there are only inferences on the numbers of lower-mass black holes (e.g. Wyithe & Loeb 2003; Bromley et al. 2004).

With this noted, however, we are encouraged to compute what black hole masses the X-ray limits in Table 1 imply, assuming that these putative black holes are actually active. For the purposes of this calculation, we scale the bolometric luminosity to the Eddington luminosity, as $L_{\mathrm{bol}} = \eta_{\mathrm{Edd}} L_{\mathrm{Edd}}$. Since our observations are in a restricted energy band, we use a fiducial SED template (Sazonov et al. 2004) to calculate the fraction of the total energy in the relevant band, f_{b} (the inverse of which is the usual bolometric correction factor). Then the luminosity in band b is $L_{\mathrm{X,b}} = f_{\mathrm{b}} \eta_{\mathrm{Edd}} L_{\mathrm{Edd}}$, or

$$L_{\mathrm{X,b}} = 2.52 \times 10^{42}\,(f_{\mathrm{b}}/0.02)\,(\eta_{\mathrm{Edd}}/1.0) \times$$
$$(M_{\mathrm{bh}}/10^{6}\,M_{\odot})\,\mathrm{erg\,s}^{-1}, \qquad (1)$$

where $f_{\mathrm{b}} \approx 0.02$ is calculated for the observed soft-band at $z \approx 5.8$ directly from the template. Assuming the best case of $\eta_{\mathrm{Edd}} \approx 1.0$ (e.g. Floyd 2004), we find an upper limit on the average mass of *active* black holes in each galaxy of

$$M_{\mathrm{bh}} < 3.3 \times 10^{6}\,(f_{\mathrm{b}}/0.02)^{-1}\,(\eta_{\mathrm{Edd}}/1.0)^{-1}\,M_{\odot}\,(3\,\sigma). \quad (2)$$

Integrating the Sazonov et al. (2004) template between $1\text{--}4\,\mathrm{ryd}$ (between the H I and He II edges), we find an energy fraction of $f_{\mathrm{UV}} \approx 0.056$. The production rate limit of H I-ionizing photons per galaxy is then $\dot{N}_{\mathrm{ioniz}} < L_{\mathrm{X}} (f_{\mathrm{UV}}/f_{\mathrm{b}})/\langle h\nu \rangle \approx 4.0 \times 10^{53}\,\mathrm{s}^{-1}$. Considering the ensemble of galaxies and the approximate relevant volume, we estimate the ionizing photon rate density

$$\dot{n}_{\mathrm{ioniz}} < 2.0 \times 10^{51}\,\mathrm{s}^{-1}\,\mathrm{Mpc}^{-3}\,(3\,\sigma). \qquad (3)$$

5. DISCUSSION

If remnants from $z \approx 20$ $M_{\rm st} \sim 100\,M_\odot$ population III stars form the seeds of early black holes, which then grow through radiative accretion until $z \approx 6$, they would have masses $M_{\rm bh} \approx 10^{5-6}\,M_\odot$, even for a large $\epsilon \approx 0.3$ and before considering merging. However, at the limit of Eq. 2, the density of (active) black hole mass inferred is $\rho_{\rm bh,6} < 1.5 \times 10^4\,M_\odot\,{\rm Mpc}^{-3}$, which is much smaller than the present-day density of all black holes, $\rho_{\rm bh,0} = 2.9 \times 10^5\,M_\odot\,{\rm Mpc}^{-3}$ (Yu & Tremaine 2002). Therefore, the present limit is plausible, while allowing great latitude for black holes to continue to grow (and shine).

For full (hydrogen) ionization, the ionization rate (Eq. 3) must exceed the recombination rate, $\dot{n}_{\rm recomb} = C\,\alpha_{\rm B}\,n_{\rm H}(z)^2$, where $C = \langle n_e^2 \rangle / \langle n_e \rangle^2$ is the clumpiness of the ionized gas, $\alpha_{\rm B} \approx 2.6 \times 10^{-13}\,{\rm cm^3\,s^{-1}}$ is the (case B) recombination coefficient for a temperature $T \approx 10^4\,{\rm K}$, and $n_{\rm H}(z)$ is the particle density of hydrogen. Then,

$$\dot{n}_{\rm recomb} = C\,\alpha_{\rm B}\,[(1 - Y_{\rm He})\,n_{\rm b,0}\,(1+z)^3]^2$$
$$= 3.2 \times 10^{52}\,(C/1.0)\,{\rm s^{-1}\,Mpc^{-3}}, \qquad (4)$$

where $n_{\rm b,0} = 2.7 \times 10^{-7}\,{\rm cm^{-3}}$ (Spergel et al. 2003) is the present-day density of baryons, and $Y_{\rm He} \approx 0.24$ is the primordial He fraction. Estimates and simulations suggest that the clumpiness is $C \approx 1\text{--}30$ (Madau et al. 1999; Cen 2003). Therefore, even at the upper limit of Eq. 3, active black holes associated with luminous galaxies cannot be responsible for but a small fraction of the total ionizing flux at $z \approx 6$. Most changes to the calculations would be in the sense of *decreasing* the $\dot{n}_{\rm ioniz}/\dot{n}_{\rm recomb}$ ratio. Cosmic variance (Barkana & Loeb 2003; Somerville et al. 2004) could affect these results by a factor of two. The surface density of the $z \approx 6$ galaxies used here is, however, consistent with results from independent fields (Bouwens et al. 2003).

It is worth noting that if the SED of an accreting $M_{\rm bh} \lesssim 10^6\,M_\odot$ black hole is *harder* than the Sazonov et al. (2004) template, as has been argued e.g. by Madau et al. (2004), the X-ray limit derived above would imply *fewer* ionizing UV photons. Such

sources may still be playing an important role with partial ionization (especially if they are not explicitly associated with luminous galaxies), or may be instrumental in achieving the early reionization suggested by WMAP (e.g. Somerville et al. 2003; Madau et al. 2004).

Our results are consistent with Dijkstra et al. (2004), who use the observed soft X-ray background to infer the maximum contribution to the rest-frame hard X-ray background at $z > 6$, and based on strong observational limits, rule out a significant contribution to the ionizing flux by active accreting black holes.

Based on a self-regulated prescription for the growth of black holes in a ΛCDM framework, Wyithe & Loeb (2003) motivate the local Magorrian et al. (1998) relation, and make predictions for massive black holes as a function of redshift. Their predicted number counts of active black holes at high redshift are shown in Figure 2, with the data from this work. This shows that useful constraints on such ΛCDM models will be possible with only a few times larger survey areas, even at sensitivities comparable to the present CDF-S. The Wyithe & Loeb (2003) black hole mass function (see their fig. 5) predicts a cumulative black hole number density of $n_{\rm bh} \approx 9 \times 10^{-4}\,{\rm Mpc}^{-3}$ down to $M_{\rm bh} \approx 3 \times 10^6\,M_\odot$, which is about five times smaller than the upper limit from our sample. This suggests that, distinct from the census of ionizing photons from such sources, larger deep *Chandra* surveys in fields with large high-redshift galaxy samples may achieve stronger constraints on the models. Future X-ray missions, such as *Constellation-X* and *XEUS* will easily reach the relevant sensitivities – if any black holes driving "mini-quasars" at $z \approx 6$ are there to be found at all.

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